

Ultra- and Extremely High Energy Neutrino Astronomy

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Abstract — Scientific motivations for ultra- and extremely high energy neutrino astronomy are considered. Sources and expected fluxes of EHE/UHE neutrinos are briefly discussed. Operating and planned experiments on astrophysical neutrino detection are reviewed focusing on deep underwater/ice Cherenkov neutrino telescopes.

1 Introduction

From cosmic ray studies, there is a clear evidence that energies of primary cosmic rays extend up to enormous energies of more than 10^{20} eV with highest energy cosmic rays detected by Fly's Eye (HiRes) collaboration [1, 2], Yakutsk air shower array [3] and the AGASA experiment [4]. At the same time, the highest energy cosmic rays represent still a *terra incognita* with respect to the processes powering them. The key question of modern astrophysics - namely, *What is the nature of the cosmic high energy world?* - has to be considered as unsolved. There is no probe except for neutrino which could help us to answer this question. Electrically charged protons and heavier nuclei, whose arrival direction is scrambled by galactic and intergalactic magnetic fields, are able to point back to the sources of their acceleration only above approximately $1-10 \text{ EeV}^1$. γ -rays keep the initial direction but the Universe is not transparent for them at energies above TeV range since they annihilate into electron-positron pairs in an encounter with a 2.7 K cosmic microwave background photons or with infra-red radiation. For example, γ -quantum of 1 PeV energy can not reach us even from the Galaxy center (10 kpc). Neutrons are too short-live particles and they are not in time to cross even our Galaxy before decaying if their energy is below several EeV. Thus, neutrino remains the only *i)* weak interacting; *ii)* stable; and *iii)* neutral probe which can reach the Earth (where we are able to observe it) from the cosmological distances keeping original direction and pointing back to the source of its origin, meeting thus the basic requirements of *astronomy*.

MeV-range neutrino astronomy have been existing for forty years with two neutrino sources identified so far, namely the Sun and Supernova SN-1987A, which at the moment remain the only two experimentally proved extraterrestrial neutrino sources. Development of ultra- and extremely high energy ²⁾ neutrino astronomy is under way, being still in its infancy. It started in 1960 with academician Markov's suggestion to use a natural basins (lakes or seas) to deploy there a large volume neutrino telescopes [5]. The large instrumented volume is needed due to the two basic reasons: firstly, expected fluxes of UHE/EHE neutrinos are very low and, secondly, cross section of neutral current (NC) and charged current (CC) neutrino interactions $\nu_l N \xrightarrow{NC(CC)} \nu_l(l) X$ (by which neutrinos are supposed to be detected) is small despite its increase with the neutrino energy. To detect neutrinos associated with highest energy cosmic rays one needs a kilometer scale detectors. After the first experimental steps at the middle of the 1970th (the DUMAND project [6]) and detection of the first 'underwater' atmospheric neutrino at the middle of the 1990th (the BAIKAL experiment [7]) experimental groups and collaborations moved to the next stage: creation of detectors with effective areas of 0.1 km^2 and higher with an ultimate goal to build neutrino telescopes with effective volumes of one cubic kilometer.

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¹⁾ Let us remind the energy units relevant to the discussed topic: $1 \text{ GeV} = 10^9 \text{ eV}$, $1 \text{ TeV} = 10^{12} \text{ eV}$, $1 \text{ PeV} = 10^{15} \text{ eV}$, $1 \text{ EeV} = 10^{18} \text{ eV}$, $1 \text{ ZeV} = 10^{21} \text{ eV}$, correspondingly.

²⁾ Ultrahigh energy range (UHE) is $E_\nu = 30 \text{ TeV} - 30 \text{ PeV}$; extremely high energy range (EHE) is $E_\nu > 30 \text{ PeV}$, respectively.

This talk reviews the physical goals and experimental status for ultra- and extremely high energy neutrino astronomy focusing, first of all, on operating and planned deep underwater/ice Cherenkov neutrino telescopes.

2 Detection Principles and Scientific Goals

Underwater/ice neutrino telescopes (UNTs) represent a 3-D arrays of photomultipliers deployed deep in the lake, ocean or in the polar ice at the depth of 1 to 4 kilometers to provide with a shield against the sun and moon light background and background of atmospheric muons. Detection principle is based on registration of the Cherenkov photons emitted by charged leptons (including those emitted by secondaries produced along their way in the water or ice and by their decay products) which are generated in CC neutrino interactions $\nu_l N \xrightarrow{CC} l X$ (see Fig. 1). Also hadronic showers produced in NC neutrino interactions $\nu_l N \xrightarrow{NC} \nu_l X$ inside UNT sensitive volume can be

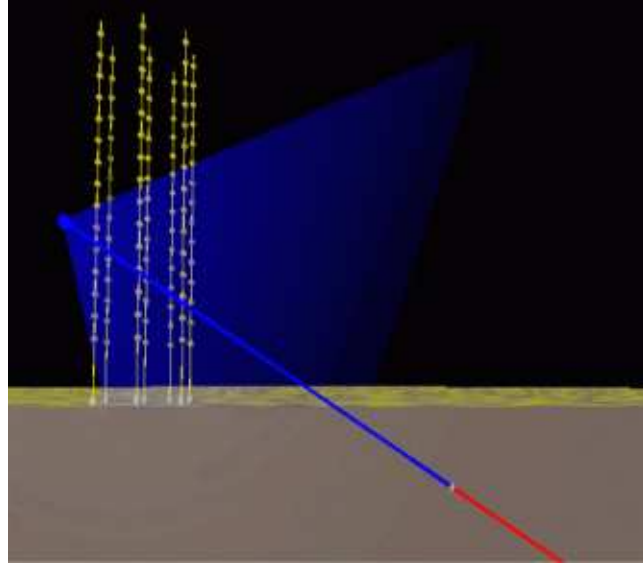


Figure 1: Neutrino detection in an UNT (schematic view)

detected by radiated Cherenkov photons. PMT hit times and positions provide with a possibility to reconstruct the track or shower vertex while a charge collected on PMT anodes allows to reconstruct the energy.

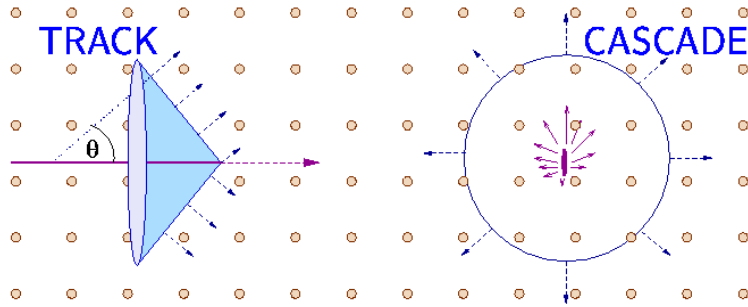


Figure 2: Two event topologies in an UNT (schematic view).

Thus, there can be two main event topologies in UNTs (Fig. 2):

- **track event** in case of muon of any energy or tau-lepton with energy $E_\tau \gtrsim 2 \text{ PeV}$ (approximately above this energy tau-lepton is able to propagate remarkable distance before decay thanks to the Lorentz factor);
- **shower event** in case of electron, tau-lepton with energy $E_\tau \lesssim 2 \text{ PeV}$ and NC interactions of all flavor neutrinos.

However, real events may contain both topologies. Track of UHE/EHE muon or tau-lepton is complemented by showers produced by secondaries which are generated in the muon interactions: bremsstrahlung, direct e^+e^- -pair production, photonuclear interactions and knock-on electron production. With some probability these showers can take the major fraction of μ/τ energy and even all the energy (first of all due to bremsstrahlung). Thus, a combined topology **track+shower** takes place. As well as, a tau-lepton track with a subsequent decay create such combined topology. CC muon neutrino (or tau neutrino if E_{ν_τ} is in multi-PeV range or higher) interaction within UNT sensitive volume with an hadronic shower in the neutrino interaction vertex and subsequent charged lepton track also produces a combined topology which is even more complex in case of tau-lepton if it decays inside sensitive volume providing thus with at least two showers: in neutrino interaction point and at the decay point (so called 'double bang' [8]). On the other hand, at energies below PeV range two showers at the tau neutrino interaction vertex and at the tau-lepton decay point are so close to each other that can not be separated at reconstruction (also tau-lepton track can not be distinguished) and thus, such an event can be considered as a pure shower one.

The main goal of UHE/EHE neutrino astronomy is to determine the origin of high energy cosmic rays. For this it is needed to detect natural flux of the high energy neutrinos measuring neutrino energy, directional information and intensity. Expected sources of UHE/EHE neutrinos are as follows (more detailed review can be found, e.g., in [9]):

- steady sources like, e.g., Active Galactic Nuclei (AGN), Supernova Remnants (SNR) or microquasars;
- transient sources like Gamma Ray Bursts (GBR);
- decay of superheavy particles or topological defects.

Detection of UHE/EHE neutrinos and identification of their sources would allow to clarify the origination of UHE/EHE cosmic rays and to understand the processes by which the nature fills the Universe with the highest energy particles.

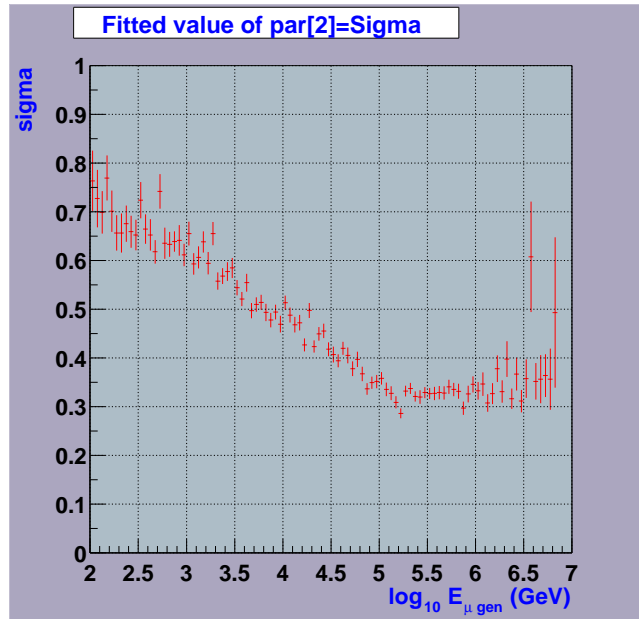


Figure 3: Energy resolution of the ANTARES 12-string detector (see Sec. 4.5) which is planned to be deployed by 2007 (taken from [10]): sigma of the distribution of $\log_{10}(E_\mu^{rec}/E_\mu^t)$ versus E_μ^t .

Accuracy of energy measurements in UNTs is not too high. Energy reconstruction is based on the increase of emitted Cherenkov light due to muon (τ) catastrophic energy losses above ≈ 1 TeV. Also, amount of Cherenkov photons produced by both hadronic and electromagnetic shower is more or less proportional to the shower energy. But due to stochastic nature of energy losses and due to the fact that an UNT represent a non-dense detector with PMTs spaced by typically 10-100m, UNTs can not be a good calorimeter: for instance, dispersion of the $\log_{10}(E_\mu^{rec}/E_\mu^t)$ distribution (where E_μ^t is the true muon energy and E_μ^{rec} is the reconstructed energy, respectively) is around $\sigma \approx 0.5$ at $E_\mu \sim 5$ TeV and $\sigma \approx 0.3$ for $E_\mu \gtrsim 100$ TeV which means that the muon energy resolution is

at the level of 2-3 only (see Fig. 3). Besides, an additional un-avoided error at neutrino energy measurement comes from the fact that fraction of energy that is taken by charged lepton at neutrino CC interaction has a distribution and if neutrino interaction occurs far apart UNT sensitive volume and, hence, shower energy can not be reconstructed, reconstructed charged lepton energy is not a good estimator for the neutrino energy.

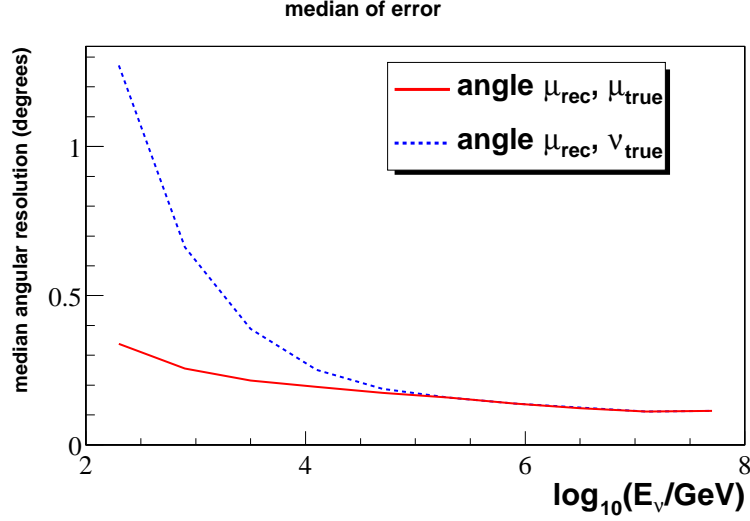


Figure 4: Angular resolution of the 12-string ANTARES detector versus E_ν (taken from [10]): median of the distribution of the angle in space between the reconstructed muon track and the true muon track (solid) or the parent neutrino track (dashed). Below $E_\nu \approx 10$ TeV the reconstruction error is dominated by $\nu - \mu$ kinematics, at higher energies accuracy is limited only by PMT TTS and light scattering.

Angular resolution for track events at UHE/EHE range is, typically, at $\sim 0.1^\circ - 1.0^\circ$ level (Fig. 4) and it is sufficient for search of point-like neutrino sources.

The first main background for neutrino events comes from down-going atmospheric muons and it is suppressed by putting UNT as deeper as possible to provide with a shield of water or ice (each 1 km of water suppress the atmospheric muon background by approximately one order of magnitude) and by selecting of up-going events as neutrino candidates. The second background is due to atmospheric neutrinos. The flux of astrophysical neutrinos is expected to behave like $E_\nu^{-2.0}$ whereas the atmospheric neutrino spectrum falls like $E_{\nu_{atm}}^{-3.7}$, yielding a better signal-to-background ratio at higher energies. Thus, atmospheric neutrino background can be suppressed by setting the off-line energy threshold at the level $E_{thr} \sim 10\text{-}100$ TeV.

Except for deep underwater or ice neutrino detection other techniques are also discussed and used (for more detailed review see [11]):

- detection of coherent Cherenkov radio waves emitted by electromagnetic showers [12];
- acoustic pulses generated in matter heated by UHE/EHE cascades due to ionization energy losses [13];
- detection of neutrino interactions by horizontal air showers (both with traditional Earth-based large extensive air shower arrays [14] and with satellite space-based detectors [15]).

Such kind of experiments have a high energy thresholds (at EeV energy range) and are aimed to detection of highest energy neutrinos. Target masses for neutrino interaction are at the level of Giga-tons and higher providing with opportunity to detect weak neutrino fluxes.

3 Predicted Fluxes and Bounds

All the models for generation of UHE/EHE particles can be divided roughly by two main classes.

Bottom-up models consider initially low energy particles which are accelerated up to UHE/EHE, typically, by shock waves propagating in accretion disks around black holes or along the extended jets emitted perpendicularly

to the disk. Neutrino are supposed to be produced in decays of mesons which are generated by interaction of accelerated particles with surrounding matter or photon fields. Such models predict $E_\nu^{-2.0}$ behavior of neutrino spectrum. By normalization of the neutrino flux to the known cosmic ray flux one can obtain an upper bound of $dN/dE_\nu \sim 5 \times 10^{-8} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (Waxman-Bahcall limit [16]) to the neutrino flux integrated over all possible sources or *diffuse* neutrino flux (Fig. 5). More detailed consideration which involves, in particular, the source transparency, leads to bounds at the level between the Waxman-Bahcall limit and $dN/dE_\nu \sim 10^{-6} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ ([17], 'MPR obscured' and 'MPR transparent' in Fig. 5). The last flux value more or less corresponds to the best experimental limits set by the moment on diffuse neutrino flux.

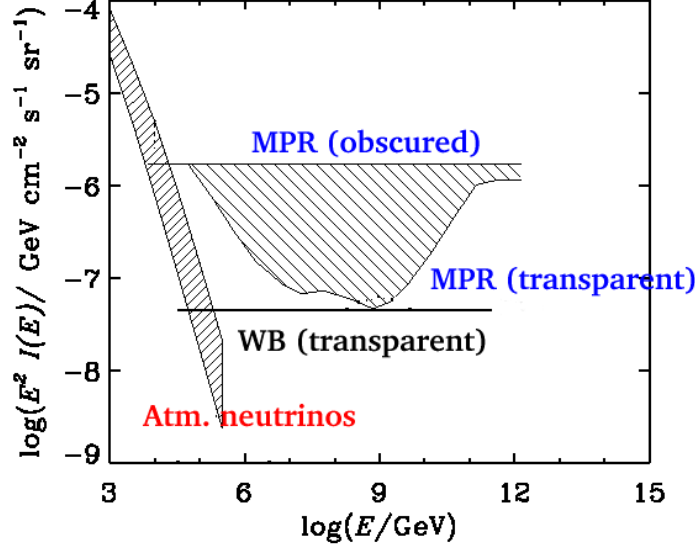


Figure 5: Waxman-Bahcall ([16], line marked 'WB') and Mannheim-Protheroe-Rachen ([17], lines marked 'MPR obscured' and 'MPR transparent') limits on diffuse neutrino flux. Atmospheric neutrino flux is shown at the left, as well (the strip corresponds to different zenith angles).

In so called *top-down* scenarios particles are not accelerated but, instead, are born with high energies in decays of super-massive particles which generate UHE/EHE nucleons, γ -rays and neutrinos.

Different predictions for neutrino fluxes generated in different sources (see, e.g., [18]) lead to expected flux at the Earth at the level of $\sim 100 \text{ event yr}^{-1} \text{ km}^{-2}$ above $E_\nu > 10 \text{ TeV}$.

4 Underwater/ice Neutrino Projects

The neutrino telescope word map is shown in Fig. 6.

4.1 DUMAND

The first project for deep underwater Cherenkov neutrino detection, DUMAND (Deep Underwater Muon and Neutrino Detector [6]) existed from about 1976 through 1995. The goal was the construction of the detector, to be placed at 4800 m depth in the Pacific Ocean off Keahole Point on the Big Island of Hawaii. Many preliminary studies were carried out, from technology to ocean optics. A prototype vertical string of instruments suspended from a special ship was employed to demonstrate the technology, and measure the cosmic ray muon flux in the deep ocean. The DUMAND hardware was donated to the NESTOR Project in Greece (Sec. 4.4), and may yet be employed there. Although the DUMAND project was canceled in 1995, it stimulated a lot the development of underwater technique for neutrino detection.

4.2 Baikal

The Baikal neutrino detector is located at a depth of 1100 m in Siberian Lake Baikal. The experiment started in early 80th, the first stationary single-string detectors equipped with 12-36 PMTs were put in operation in 1984-86. In 1993 the Baikal collaboration was the first to deploy pioneering 3-D underwater array consisting of 3 strings (as

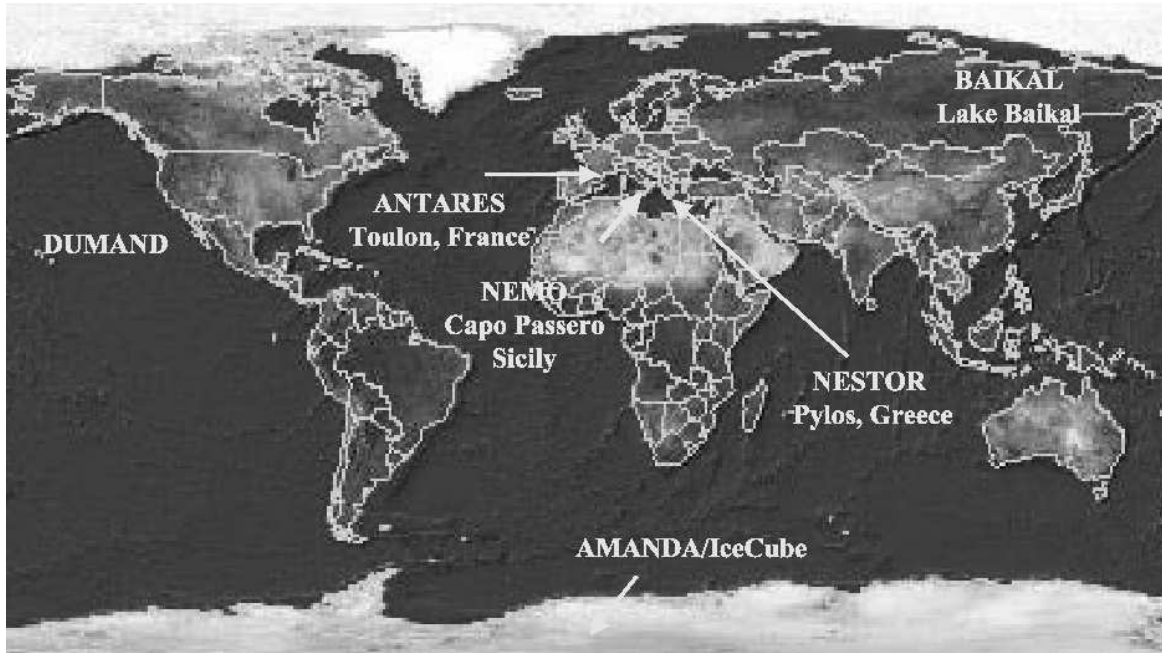


Figure 6: The neutrino telescope world map

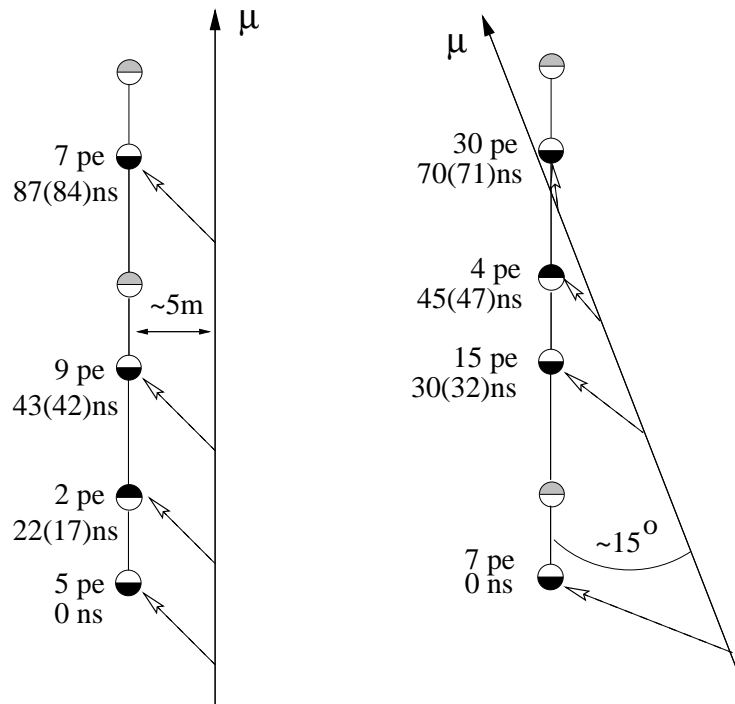


Figure 7: The first two atmospheric neutrinos detected underwater in the Baikal experiment in 1994. The hit PMTs are marked in black. Numbers give the measured amplitudes (in photoelectrons) and measured (expected) times with respect to the first hit channel.

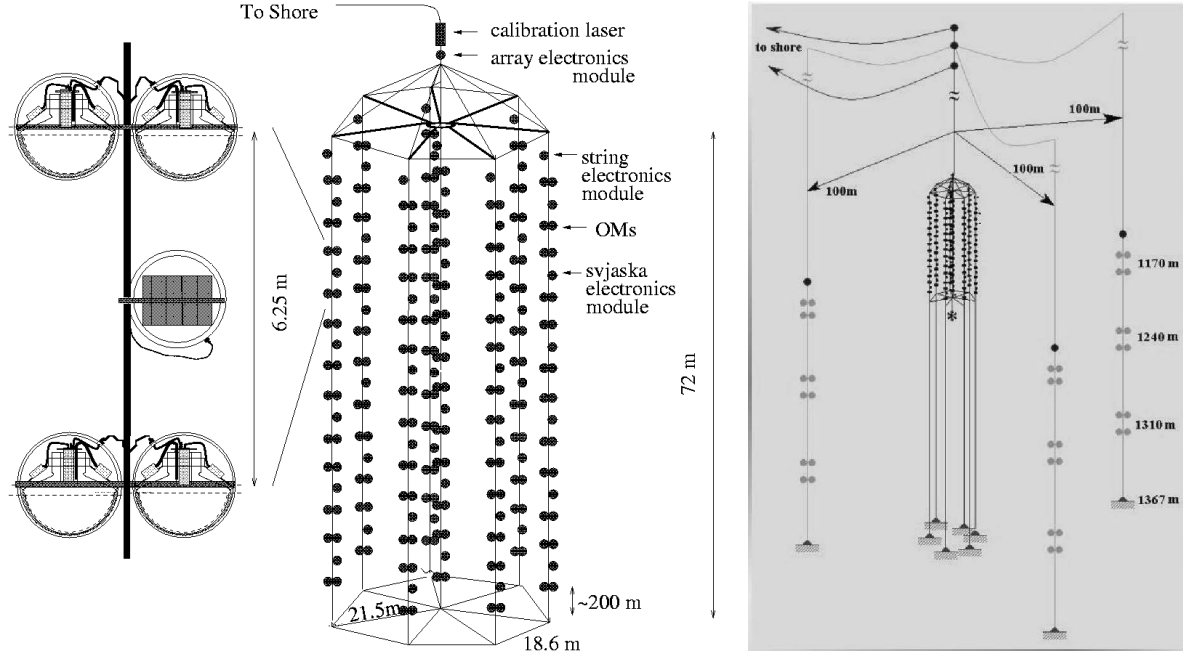


Figure 8: The Baikal neutrino telescope NT-200 (left) and its planned upgrade NT-200+ (right)

necessary for full spatial reconstruction). In 1996 the first atmospheric neutrinos detected underwater (see Fig. 7) were reported [7].

Since 1998 8-string NT-200 detector equipped with 192 15" PMTs is taking data (Fig. 8). An upgrade (NT-200+) is under construction and it is planned to be completed by 2005. NT-200+ will consist of NT-200 surrounded by 3 additional strings placed 100m apart and it is optimized for diffuse neutrino flux detection. The current limit on diffuse neutrino flux set by the Baikal experiment is $dN/dE_\nu \sim 1.3 \times 10^{-6} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for energy range $10 \text{ TeV} \leq E_\nu \leq 10 \text{ PeV}$ (assuming E_ν^{-2} neutrino spectra). Besides, limits on magnetic monopole flux, Q-ball flux, results on search of neutralinos in the core of the Earth, measurements on atmospheric muons and neutrinos were reported [19].

4.3 AMANDA/IceCube

The first antarctic detector AMANDA-B10 was put into operation at the beginning of 1997. It consists of 302 PMTs deployed at a depth 1500-2000m. AMANDA (Antarctic Muon and Neutrino Detector Array) collaboration uses 3 km thick ice layer at the geographical South Pole. Holes are drilled with hot water and then strings with PMTs are frozen into the ice. In January 2000 deployment of additional 9 strings was completed and since that time AMANDA-II detector is in operation with 677 PMTs at 19 strings (see Fig. 9). The unique feature of AMANDA is that it continuously works in coincidence with surface air shower experiment SPASE [20] which allow to calibrate the angular resolution. Given a E_ν^{-2} benchmark neutrino spectral shape, limits $dN/dE_\nu \sim 1.5 \times 10^{-6} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and $dN/dE_\nu \sim 0.86 \times 10^{-6} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ are set on diffuse neutrino flux in the ranges $1 \text{ PeV} \leq E_\nu \leq 3 \text{ EeV}$ and $50 \text{ TeV} \leq E_\nu \leq 5 \text{ PeV}$, respectively [21]. Estimated sensitivity to the point-like neutrino sources is at the level of expected neutrino fluxes from AGNs Mrk421 and Mrk501 [22], as well as from microquasar SS433 for a specific model [23]. Also results on atmospheric muons and neutrinos, WIMP and magnetic monopoles search, search for supernovae bursts, primary cosmic ray composition have been published by the AMANDA collaboration [24].

As a next step of development of the neutrino observatory at the South Pole creation of neutrino telescope with instrumented volume of 1 km^3 (IceCube) is foreseen [25]. It will consist of 4800 PMTs deployed on 80 vertical strings (each of 60 PMTs) at the depth from 1400 m to 2400 m. The distance between strings is 125 m, the distance between PMTs along the strings 16 m. Existing detector AMANDA-II will be integrated to IceCube. Fig. 10 gives a schematic view of IceCube and its position with respect to AMANDA-II and the air shower array. Deployment operations at the South Pole will begin in late 2004 and detector will be completed by 2010. With 45,000 atmospheric neutrinos recorded per year the ultimate sensitivity to an extraterrestrial E_ν^{-2} neutrino flux after 3 years of data taking is $dN/dE_\nu \sim 3(10) \times 10^{-9} E_\nu^{-2} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ (the first number refers to the 90% limit

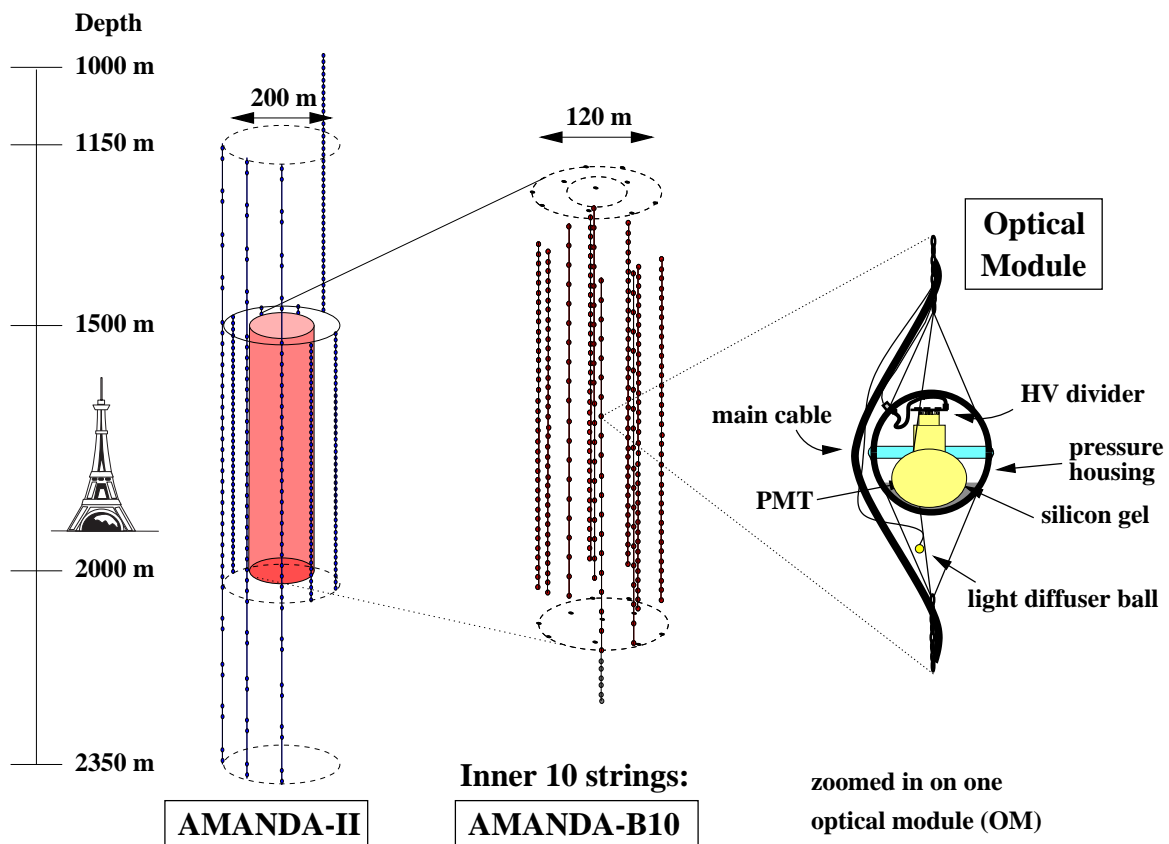


Figure 9: The AMANDA detector. The scheme is illustrated by Eiffel tower at the left. Each dot represents an optical module with PMT.

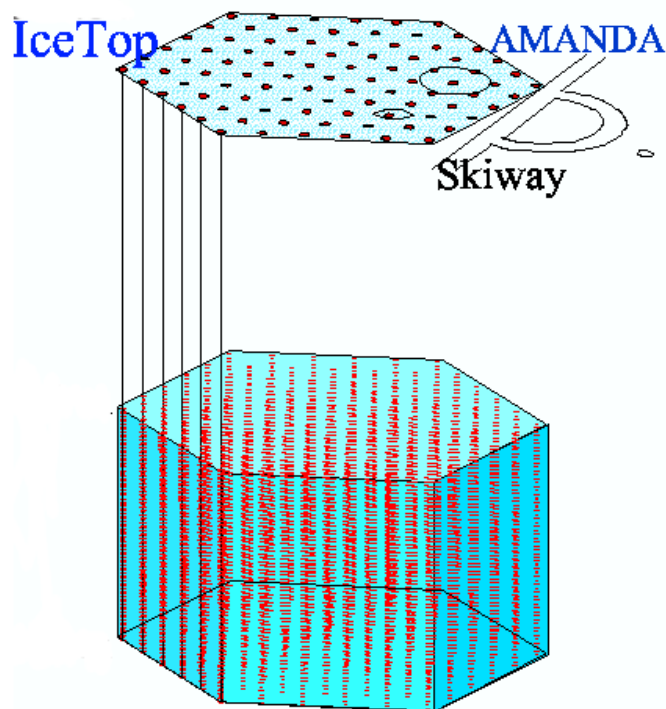


Figure 10: Schematic view on the future IceCube detector

and the second one to the 5σ sensitivity). This is lower compared to Waxman-Bahcal and Mannheim-Protheroe-Rachen upper bounds [16, 17] and to the most popular predictions on diffuse neutrino flux which are based on different models [18].

4.4 NESTOR

NESTOR (Neutrino Extended Submarine Telescope with Oceanographic Research) [26] will be deployed in the Mediterranean Sea, near Pylos (Greece) at 4 km depth. It is planned to be 'tower based detector' (Fig. 11). Each

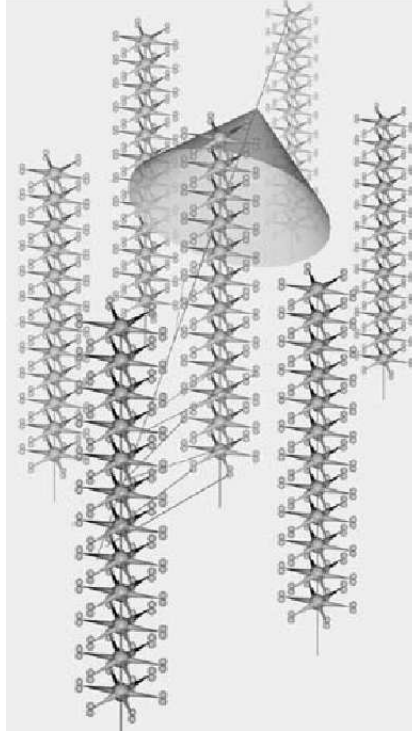


Figure 11: Schematic view of the NESTOR detector

tower consists of 12 hexagonal floors spaced by 30 m with 6 pairs of up-down looking 15" PMTs each. The diameter of the floor is 32 m. The effective area of the tower with respect to TeV-range muons is about 0.02 km^2 . The NESTOR collaboration has passed through a long phase of site evaluation and technology tests. An 28 km electro-optical cable was put on the seafloor to connect the detector and shore station in 2000 and it was repaired in 2002. In March, 2003 a 'prototype floor' equipped with 12 PMTs was deployed. Over 5 millions of muon triggers were recorded during its operation.

4.5 ANTARES

The ANTARES project [27] (Astronomy with a Neutrino Telescope and Abyss environmental Research) was formed in 1996. In 1996-99 an intense R&D program was performed. The deployment and recovery technologies, electronics and mechanical structures were developed and tested with more than 30 deployments of autonomous strings. The environmental properties at the detector site were investigated. ANTARES R&D program culminated with deployment and 8 month operation of a 350 m length 'demonstrator string' (November 1999 - July 2000) instrumented with 7 PMTs at a depth of 1100 m, 40 km off the coast of Marseille. The string was controlled and read out via 37 km-long electro-optical cable connected to the shore station. $\sim 5 \cdot 10^4$ seven-fold coincidences from atmospheric muons were recorded. The angular distribution of atmospheric muons was reproduced and the fraction of multi-muon events was found to be in agreement with expectation.

After extensive R&D program the collaboration moved into construction of a 12-string detector in the Mediterranean Sea at 2400 m depth, ~ 40 km off-shore of La Seyne sur Mer, near Toulon ($42^\circ 50' \text{ N}$, $6^\circ 10' \text{ E}$). Each string will be instrumented with 75 PMTs housed in glass spheres (see Fig. 12). PMTs are grouped in triplets at 25 levels separated by 14.5 m. 3 PMTs in each triplet are oriented at 45° to the nadir. Strings are separated from each

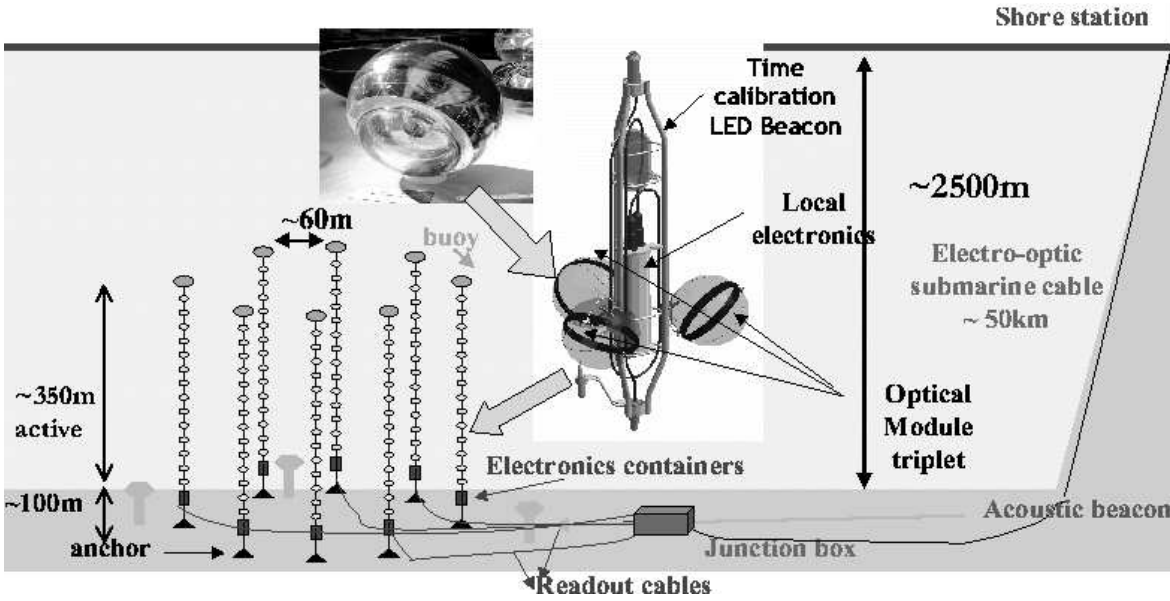


Figure 12: Schematic view of the ANTARES 12-string detector

other by ~ 70 m. All the strings are connected to a Junction Box (JB) by means of electro-optical link cables. The JB is connected to the shore station by a 50 km length 48-fiber electro-optical cable. Undersea connections are performed with a manned submarine. The deployment of the detector is planned for 2005-2007. The important milestones that have been achieved by the collaboration are:

- the electro-optical cable connecting detector and shore station was deployed in October 2001;
- the industrial production of 900 OM's started in April 2002;
- since December 2002 the JB is in communication with the shore station;
- in December 2002 and February 2003 the 'prototype instrumentation string' and the 'prototype detection string' (equipped with 15 OM's) were successfully deployed (recovered in May and July, 2003, respectively);
- in March 2003 both strings were connected to JB with the Nautile manned submarine and data taking started.

The sensitivity of the detector to diffuse neutrino fluxes achieved by rejecting the background with an energy cut of $E_{cut} = 50$ GeV allows to reach Waxman-Bahcall limit in 3 years. The ANTARES sensitivity for point-like source searches (90% C.L.) assuming E^{-2} differential ν flux is in the range $4 \div 50 \cdot 10^{-16} \text{ cm}^{-2} \text{ s}^{-1}$ (depending on the source declination) after 1 year, which gives a real hope to detect a signal from the most promising sources.

The deployment of the ANTARES neutrino telescope can be considered as a step toward the creation of a 1 km^3 detector in the Mediterranean Sea.

4.6 NEMO

NEMO [28] (NeuTrino subMarine Observatory) is an R&D project of the Italian National Institute for Nuclear Physics (INFN) for 1 km^3 neutrino underwater telescope to be deployed in Mediterranean Sea near Capo Passero, Sicily, at the depth of 3500 m where transparency and other water parameters are optimal. At the first stage (1998-2000) the NEMO collaboration performed an intensive search program (more than 20 sea campaigns) to determine the optimal site for the future detector. Also R&D program on materials, PMTs and mechanical components of the detector were performed. At the second stage which started in 2002, the advanced R&D and prototyping is done. The laboratory which is connected with test site of-shore Catania by 28 km electro-optical cable is used for this purpose. The overall number of PMTs in NEMO detector may lay between 7000 and 10000.

5 Conclusions

“...because then we might find something
that we weren't looking for, which might
be just what we were looking for, really...”

A. Milne, “Winnie-The-Pooh” [29]

Thus, during the next decade several 0.1–1.0 kilometer scale underwater (ice) Cherenkov neutrino telescopes will be put into operation both in Southern and North Earth hemispheres being complemented by other technique detectors (radio, acoustic, air showers). Expected sensitivity of these detectors to extraterrestrial neutrino fluxes (see Fig. 13) gives a hope to open a new era in UHE/EHE neutrino astronomy by detection of high energy neutrino signal. Both discovering and *not* discovering of extraterrestrial UHE/EHE neutrinos will help to solve one of the oldest astrophysical puzzle - *origin of highest energy cosmic rays*. But hopefully, it will also lead to discovery of new unexpected phenomena and setting new puzzles that will have to be solved with next generation detectors and next generation of scientists.

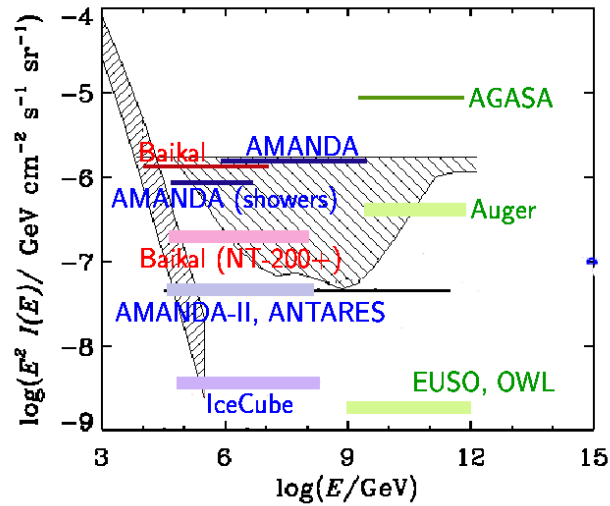


Figure 13: Present limits (horizontal solid lines) on diffuse extraterrestrial neutrino flux and expected sensitivity to neutrino fluxes (horizontal strips), assuming E^{-2} behavior of neutrino spectrum, for operating and planned UHE/EHE neutrino experiments. Upper bounds on diffuse neutrino fluxes and atmospheric neutrino spectrum are given, as well (see caption to Fig. 5).

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